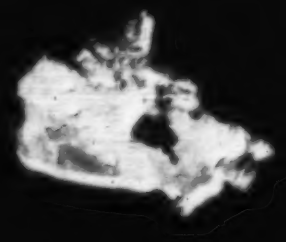
CFS CANADIAN FOREST SERVICE
SCF SERVICE CANADIEN DES FORÊTS
cfs-scf.nrcan-rncan.gc.ca



Calculating risk of mountain pine beetle attack: comparison of distance- and density-based estimates of beetle pressure

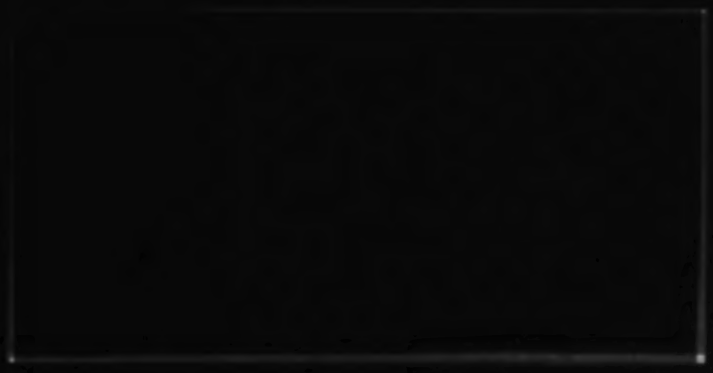
Michael A. Wulder[1], Joanne C. White[1], Caren C. Dymond[1], Trisalyn Nelson[2], Barry Boots[3], Terry L. Shore[1]

Mountain Pine Beetle Initiative Working Paper 2007-11

Natural Resources Canada, Canadian Forest Service,
Pacific Forestry Centre, 506 West Burnside Road, Victoria, BC V8Z 1M5
(250) 363-0600 • www.pfc.cfs.nrcan.gc.ca

Natural Resources Canada | Ressources naturelles Canada

Canada



Canada

Mountain Pine Beetle Initiative
Canadian Forest Service

Calculating risk of mountain pine beetle attack: comparison of distance- and density-based estimates of beetle pressure

Michael A. Wulder[1], Joanne C. White[1], Caren C. Dymond[1], Trisalyn Nelson[2], Barry Boots[3], Terry L. Shore[1]

Mountain Pine Beetle Initiative Working Paper 2007-11

MPBI Project #6.01

[1] Natural Resources Canada
Canadian Forest Service
Pacific Forestry Centre
Victoria, BC V8Z 1M5

[2]University of Victoria
Department of Geography
Victoria, BC V8W 2Y2

[3]Wilfrid Laurier University
Department of Geography and Environmental Studies
Waterloo, Ontario N2L 3C5

Previously published in the *Journal of Environmental Informatics* 8(2) 2006

Natural Resources Canada
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria, British Columbia V8Z 1M5
Canada

© Her Majesty the Queen in Right of Canada 2007
Printed in Canada

2007

Library and Archives Canada Cataloguing in Publication

Calculating risk of mountain pine beetle attack: comparison of distance- and density-based estimates of beetle pressure / Michael A. Wulder ... [et al.].

(Mountain Pine Beetle Initiative working paper 2007-11)
Includes bibliographic references.
ISBN 978-0-662-45133-4
Cat. No.: Fo143-3/2007-11E

Mountain pine beetle--British Columbia--Fort St. James Region. 2. Mountain pine beetle--Dispersal--British Columbia--Fort St. James Region. 3. Trees Diseases and pests Monitoring British Columbia Fort St. James Region. 4. Trees Diseases and pests British Columbia Forecasting.
Wulder, Michael A. (Michael Alberta), 1968- II. Pacific Forestry Centre III. Series.

SB945.M78A87 2007 634.9'7516768 C2007-980030-0

Abstract

An established model for risk rating of *Pinus contorta* stands for potential mortality caused by mountain pine beetle (*Dendroctonus ponderosae*) combines information on stand susceptibility and beetle pressure. Susceptibility is determined using attributes in the forest inventory data, while beetle pressure is calculated based on the size and distance to existing infestation locations (distance-based model). An alternate model for calculating beetle pressure is presented in this paper, which uses Voronoi polygons to incorporate size and distance, while emphasizing the density of existing infestation locations (density-based model), in combination with empirical knowledge of beetle dispersal and forest inventory data. Survey data of existing beetle damage were collected using a helicopter mounted global positioning system (GPS) at a study site in central British Columbia, Canada in 1999, 2000, and 2001. These data facilitated the estimation of beetle pressure, and the comparison of risk ratings to actual attack locations. Using the distance-based model, 18% and 27% of areas identified as having a risk rating of greater than 50 in 1999 and 2000 were actually found to be attacked by beetles in surveys conducted in 2000 and 2001. Conversely, 39% and 49% of areas identified as having risk greater than 50 in 1999 and 2000 with the density-based model were attacked in 2000 and 2001. The results suggest that the density-based model of beetle pressure produced risk ratings that had a greater correspondence with actual infestation occurrence than risk ratings generated from the distance-based model. Using data that is typically collected to monitor beetle populations, novel methods of spatial processing may be applied in a transparent manner, generating results that incorporate knowledge of mountain pine beetle dynamics under certain population conditions, into calculations of the risk of mountain pine beetle attack.

Key words: Voronoi diagram, modelling, mountain pine beetle, risk, beetle pressure, susceptibility, forest inventory, GPS

Résumé

Un modèle établi pour évaluer le risque de mortalité par le dendroctone du pin ponderosa (*Dendroctonus ponderosae*) menaçant les peuplements de *Pinus contorta* combine les renseignements sur la susceptibilité du peuplement et la pression du dendroctone. La susceptibilité se calcule au moyen des attributs de données de l'inventaire forestier et la pression du dendroctone se calcule en se basant sur l'ampleur et la distance des infestations par rapport aux peuplements en question (modèle basé sur la distance). Cet article décrit un autre modèle pour calculer la pression du dendroctone faisant appel à des polygones de Voronoï pour incorporer l'ampleur et la distance des infestations, tout en mettant l'accent sur la densité des infestations existantes (modèle basé sur la densité), et ce, en combinaison avec les connaissances empiriques de la dispersion du dendroctone et les données de l'inventaire forestier. On a collecté des données sur les dégâts existants infligés par le dendroctone, à l'aide d'un système mondial de positionnement (GPS) monté sur un hélicoptère, dans un site expérimental au centre de la Colombie-Britannique (Canada) en 1999, 2000 et 2001. Ces données ont facilité l'estimation de la pression du dendroctone et la comparaison des évaluations du risque par rapport aux peuplements attaqués. Avec le modèle basé sur la distance, 18 et 27 p. 100 des zones dont l'évaluation du risque était supérieure à 50 en 1999 et 2000 ont été attaquées par le dendroctone selon des études menées en 2000 et 2001. En revanche, 39 et 49 p. 100 des zones dont l'évaluation du risque était supérieure à 50 en 1999 et 2000 selon le modèle basé sur la densité ont été attaquées en 2000 et 2001. Les résultats indiquent que le modèle basé sur la densité produit des évaluations du risque plus fiables que le modèle basé sur la distance. Grâce aux données que l'on collecte habituellement pour surveiller les populations de dendroctone, on peut appliquer de nouvelles méthodes de traitement géométrique de façon transparente et générer des résultats qui intègrent les connaissances des dynamiques du dendroctone du pin ponderosa dans certaines conditions de population aux calculs du risque d'attaque par ce ravageur forestier.

Mots-clés: diagramme de Voronoï, modélisation, dendroctone du pin ponderosa, risque, pression du dendroctone, susceptibilité, inventaire forestier, GPS

Contents

1.0 **Introduction** 1
2.0 **Study area and data** 3
2.1 Study area 3
2.2 Forest inventory 4
2.3 Mountain pine beetle survey data 5
3.0 **Methods** 6
3.1 Susceptibility 6
3.2 Beetle pressure using a distance-based model 6
3.3 Beetle pressure using a density-based model 8
3.4 Stand risk 9
3.5 Correspondence to mountain pine beetle survey data 9
4.0 **Results** 10
5.0 **Discussion** 14
6.0 **Conclusion** 15
Acknowledgements 15
Contact 15
References 16

Tables

Table 1. Mountain pine beetle intensity is determined using relationships that are based on beetle populations in and near the forest stand being rated (A; after Shore and Safranyik 1992). Beetle pressure is determined based on the intensity of infestation and the proximity to the infestation, or size of the overlapping Voronoi polygon (B) 7
Table 2. Distribution of forest stands, by susceptibility rating 10
Table 3. Distribution of forest stands, by distance-based estimates of beetle pressure. 10
Table 4. Distribution of forest stands, by density-based estimates of beetle pressure 10
Table 5. Distance-based model of beetle pressure: number of stands in each class of beetle pressure and infestation status in the subsequent year 11
Table 6. Density-based model of beetle pressure: number of stands in each class of beetle pressure and infestation status in the subsequent year 11
Table 7. Risk Rating: Correspondence between 1999 and 2000 risk ratings and actual attack by mountain pine beetle in 2000 and 2001 12

Figures

Figure 1. A sample of Voronoi tessellation generated from the helicopter-GPS survey data of known mountain pine beetle infestation locations. Where the survey points are dense, the space is represented by a greater number and smaller size of Voronoi polygons. Conversely, where the survey points are less dense, the space is represented by fewer and larger polygons 2
Figure 2. The study area is located in the southern portion of the Fort St. James Forest District in central British Columbia, Canada 4
Figure 3. Examples illustrating the calculation of (A) distance- and (B) density-based models of beetle pressure. The distance-based model was generated by 1 km buffers applied to the helicopter-GPS survey points. The density-based model was generated using Voronoi polygons. The resulting beetle pressure values are shown in (C) for the distance-based model and (D) for the density-based model. 8
Figure 4. Risk ratings for 2000 generated using distance- and density-based models of beetle pressure. 13

1.0 Introduction

The mountain pine beetle (*Dendroctonus ponderosae*) is the most significant agent of mortality in mature lodgepole pine (*Pinus contorta*) forests in western North America (Furniss and Carolin 1977). The total area impacted by mountain pine beetle in the province of British Columbia, Canada, has increased from approximately 164,000 ha in 1999 to 8.5 million hectares in 2005 (Westfall 2006). Two main factors that have contributed to the successful expansion of the beetle population in British Columbia include the large amount of mature lodgepole pine on the land base, which has tripled in the last century as a result of intensive fire suppression activities (Taylor and Carroll 2004), and several successive years of favourable climatic conditions, resulting in an increase in climatically suitable areas for brood development (Carroll et al. 2004).

Adult beetles typically attack a host tree in August and lay eggs, which complete their development cycle into mature adults approximately one year later (Amman and Cole, 1983). A mass-attack by mountain pine beetle leads to tree mortality through a combination of gallery excavation and the introduction of fungal pathogens (Safranyik et al. 1974). Once killed, but while still with green foliage, the host tree is in the green attack stage. The foliage of the host tree changes colour gradually; 12 months after being attacked, more than 90% of the killed trees will have red needles (red attack; Amman 1982; Henigman et al. 1999). Three years after being attacked, most trees will have lost all needles (grey attack; British Columbia Ministry of Forests 1995). Safranyik and Carroll (2006) provide a comprehensive synthesis of our current understanding of mountain pine beetle biology.

Identifying forest stands with greatest risk for timber losses as a result of mountain pine beetle attack is critical for mitigation and forest management planning. Decision support systems that incorporate the movement of pests and disease allow managers to fight outbreaks of these phenomena more efficiently (e.g., Hawksworth et al. 1995). These systems rely on quality data sources that are suitable for informing decision making. The dispersal and population density of pests are key elements of evaluating risk; however, landscape-scale movement of pests and diseases can be difficult to measure and predict (Liu et al. 2006). The relative importance of source population density and spread distances to the evaluation of risk associated with mountain pine beetle attack has not been investigated. Rather, risk models typically rely on factors such as stand characteristics and climatic suitability (Bentz et al., 1993). Susceptibility rating systems are used by forest managers to predict the likelihood of attack and damage by mountain pine beetle. Several such systems, which use a wide range of different attributes to assess the risk of mountain pine beetle attack, have been developed in the last 30 years (Amman et al. 1977; Mahoney 1978; Berryman 1978; Schenk et al. 1980; Waring and Pitman 1980; Stuart 1984; Anhold and Jenkins 1987). Shore et al. (2006) provide details and review the merits of these various rating systems.

In the Shore and Safranyik (1992) rating system, susceptibility is a product of four factors: stand age, stand density, percentage of susceptible pine basal area in the stand, and stand location. Susceptibility ratings do not include information on the presence of existing mountain pine beetle populations (Shore et al. 2000). Therefore, a stand may have a high susceptibility to attack, but if there are no mountain pine beetles in the vicinity, the stand will not typically be at risk. Conversely, a low susceptibility to mountain pine beetle does not necessarily indicate a low likelihood of attack under epidemic population conditions (Shore and Safranyik 1992; Bentz et al. 1993); the large size of mountain pine beetle populations during an epidemic phase and the resulting increased competition for suitable hosts can result in the beetles attacking sub-optimal host trees that would otherwise not be targeted, under different population conditions (Safranyik and Carroll 2006). Because susceptibility is based on stand variables, it is typically a static rating that changes gradually, as the stand structure changes over time.

A risk rating system combines susceptibility with the location and size of nearby mountain pine beetle populations in order to characterize "the short-term expectancy of tree mortality in a stand as a result of mountain pine beetle infestation" (Shore and Safranyik 1992); or "the likelihood of an outbreak population occurring in a stand and concomitant loss during a specified period of time" (Bentz et al. 1993). The

location and size of nearby beetle populations is referred to as beetle pressure. From an operational perspective, areas identified as having a high risk rating can subsequently be assigned priority for sanitation harvesting or other mitigation activities. Beetle pressure and risk ratings are dynamic indices that can change rapidly as a result of climatic factors or beetle dispersal, and must therefore be calculated annually as new information on infestation conditions is collected (Shore and Safranyik 1992).

Knowledge of beetle pressure is an important component in assessing the risk of short-term losses in volume resulting from mountain pine beetle attack. The objective of this study is to compare two different approaches for calculating beetle pressure, and to assess the impact these approaches have on the subsequent calculation of risk ratings. To meet this objective, beetle pressure was calculated using the traditional distance-based model, as well as using an alternative density-based model, implemented with a Voronoi tessellation generated from helicopter-GPS point survey data of known beetle infestation locations. "Given a finite set of distinct, isolated points in a continuous space, we associate all locations in that space with the closest member of the point set. The result is a partitioning of the space into a set of regions" (Okabe et al. 2000). The Voronoi regions or polygons partition the space in such a way that each Voronoi polygon consists of an area that is closer to a given point than any other point. Voronoi polygons have been used for point pattern analysis in a wide range of disciplines (Boots and Getis 1988). There is an inverse proportional relationship between the size of the Voronoi polygons and the density of mountain pine beetle attack (as represented by the helicopter-GPS survey data). The representation of point density facilitated by the Voronoi polygons is intuitive: the greater the density of survey points, the smaller the Voronoi polygons. Conversely, where survey points are sparse, polygons are larger (Figure 1).

Figure 1. A sample of Voronoi tessellation generated from the helicopter-GPS survey data of known mountain pine beetle infestation locations. Where the survey points are dense, the space is represented by a greater number and smaller size of Voronoi polygons. Conversely, where the survey points are less dense, the space is represented by fewer and larger polygons.

Risk ratings were calculated for the study area using susceptibility combined with each form of beetle pressure, and these ratings were subsequently compared to survey data of known mountain pine beetle attack locations. Variations in risk ratings resulting from the methods used to estimate beetle pressure were then assessed and analyzed.

2.0 Study area and data

2.1 Study area

The study area is the southern portion of the Fort St. James Forest District in central British Columbia, Canada (Figure 2), representing approximately 10,000 square kilometres. The undulating topography ranges in elevation from 712 m to 1,394 m above sea level and is dominated by several large freshwater lakes. This area is predominantly in the Sub-Boreal Spruce biogeoclimatic zone (Meidinger and Pojar 1991). The climate of the region is continental and typically is characterized by cold, snowy winters with short, warm, moist summers. There is moderate precipitation, from 440 mm to 900 mm each year, with 25% to 50% of the precipitation occurring snow.

The productive forest is dominated by lodgepole pine and white spruce (*Picea glauca*) with trembling aspen (*Populous tremuloides*), black spruce (*Picea mariana*) and Douglas-fir (*Pseudotsuga menziezii*) as secondary species. Smaller amounts of western red-cedar (*Thuja plicata*) and sub-alpine fir (*Abies lasiocarpa*) are also found in this area. Pure and mixed stands of lodgepole pine cover most of the study region. Stands of aspen and Douglas-fir are found more frequently along the western margins of the region, while sub-alpine fir is found at higher elevations. Wildfires have left a mosaic of forest ages; lodgepole pine stands vary in age from less than 20 years to more than 250 years.

One of the epicentres of the current province-wide outbreak of mountain pine beetle was located near Fort St. James (Figure 2). Forest harvesting is the primary land-use activity in this area. In an effort to mitigate damage caused by the mountain pine beetle, the annual allowable cut in the area was initially increased by 30% in 2002 (Pedersen 2002), followed by an additional 23% increase in 2004 (Pedersen 2004). The proportion of pine volume harvested in this area has increased from 50% in 1998 (pre-epidemic) to 63% in 2005 (Pousette and Hawkins 2006).

Figure 2. The study area is located in the southern portion of the Fort St. James Forest District in central British Columbia, Canada.

2.2 Forest Inventory

Polygon-based forest inventory data are often utilized as an information source for decision support systems (Shore and Safranyik 1992). The inventory is the primary source of information on the distribution and areal extent of forest stands, logging roads, and past natural and human disturbances in the study region. Much of the information collected in the forest inventory is generated by interpretation of aerial photographs, with field visits taken to ensure the quality and consistency of interpretation. The inventory includes species composition (of up to six species, with estimates of species prevalence to the nearest 10%), stand age in years, crown closure (to the nearest 5%), stand height in metres, diameter at breast height in centimetres, and stand area in hectares (Gillis and Leckie 1993). The information in the forest inventory represents a given point in time, and the temporal cycle for inventory updates can vary (Gillis and Leckie 1996). As a result, disturbance events such as harvesting or insect outbreaks may not be captured in the forest inventory until an update is completed. In the interim, data on disturbance events is typically captured, stored, and maintained separately from the forest inventory. The forest inventory of the study area is part of the Forest Inventory Planning (FIP) database maintained by the British Columbia Ministry of Forests, and represents forest conditions in 1999. The forest inventory data were used in the calculation of susceptibility ratings.

2.3 Mountain pine beetle survey data

A hierarchy of different data sources is used to detect and map the location and extent of damage caused by mountain pine beetle infestations (Wulder et al. 2006a). Field surveys are generally conducted during the green-attack stage, when there are no visual indications of damage in foliage, but when there are symptoms of attack in the lower bole and under the bark (Safranyik and Carroll 2006). Aerial surveys are generally conducted to detect red attack damage, which is often readily discernible through visual inspection (Wulder et al. 2006b). Surveys conducted using a helicopter-mounted global positioning system (GPS) record the location and magnitude of beetle damage. The helicopter-GPS surveys capture clusters of trees with red-attack damage, and the GPS is used to record the location of the cluster centroids. For each cluster, the number of infested trees is estimated and the species of infestation recorded. The maximum area represented by a point is typically 3 ha, equivalent to a circle with a radius of 100 m (Nelson et al. 2006). While a single point is used to identify a cluster of trees, the total area, size, shape, and compactness of clusters will vary and may depend on the surveyor.

The accuracy of the helicopter-GPS surveys may be influenced by operational factors such as weather conditions, surveyor experience, and speed or flying height of the helicopter. Helicopter movement, shadow, view angle, and weather conditions may result in overestimates and underestimates of attack severity and position (Leckie et al. 2005; Wulder et al. 2006a). Helicopter-GPS surveys are considered the benchmark for operational accuracy in the detection and mapping of mountain pine beetle impacts at the local scale, with a horizontal positional accuracy of approximately 20 m and a low error of commission (< 5%; British Columbia Ministry of Forests 2004). Research has examined the uncertainty and error associated with the point estimates derived from the helicopter-GPS surveys and has indicated that errors associated with the helicopter-GPS points (as determined by direct comparison to ground surveys) were small, when estimating numbers of attacked trees, 92.6% of helicopter-GPS points have errors of ±10 trees (Nelson et al. 2006). Information from helicopter-GPS surveys conducted in the study area in 1999 and 2000 was used to generate estimates of beetle pressure, while survey data collected in 2000 and 2001 were used to assess the variation in risk ratings (generated from the previous year's survey data) resulting from the different methods of estimating beetle pressure.

3.0 Methods

The Shore and Safranyik (1992) risk index is a function of both stand susceptibility and beetle pressure. Of the two components required to rate stand-risk components, susceptibility relates to the level of damage that may occur when the stand experiences a mountain pine beetle infestation, whereas beetle pressure refers to the probability that the mountain pine beetle will enter the stand.

3.1 Susceptibility

Susceptibility to mountain pine beetle attack (*S*) was calculated as per (Shore and Safranyik, 1992):

$$S = P \times A \times D \times L \qquad (1)$$

Where *P* represents susceptible pine basal area, *A* is the age of dominant and co-dominant live pine, *D* is stand density, and *L* is a location factor based on latitude, longitude, and elevation. Index values for A, D, and L, ranging from 0 to 1, are generated and multiplied with P to produce a measure of susceptibility that ranges from 0 to 100 [see Shore and Safranyik (1992) for further details on susceptibility components and computation].

Some modifications were made to the susceptibility rating calculations to enhance the consistency of index values amongst stands. Continuous functions, rather than discrete classes, were used to calculate age, density, and location, in order to minimize abrupt differences in risk ratings caused by shifting from one discrete class to another, and to reflect developments to the model that have occurred since initial publication (Shore et al. 2006). The susceptibility model was also adapted to use the variables available in the FIP data. Specifically, the FIP data does not contain the basal area of different species, or the density (stems per hectare), which were required by the Shore and Safranyik model. The FIP adaptation replaced the percent of pine by basal area with the percent of pine by stand volume, and stand density was replaced using the quadratic mean stand diameter (breast height) as a surrogate. In addition to the forest characteristics captured in the FIP database, the latitude and longitude (in decimal degrees), and elevation (in metres) were obtained for each stand from a 25-m digital elevation model (British Columbia Ministry of Sustainable Resource Management 2002).

3.2 Beetle pressure using a distance-based model

Beetle pressure was calculated for each stand based on helicopter-GPS survey data collected in the study area in 1999 and 2000. Beetle pressure is a measure of the size and proximity of the mountain pine beetle population influencing the stand being rated. Infestations are categorized as small, medium or large, based on the size of the beetle population (Table 1). For each size category, distance to the nearest infestation is then used to compute a beetle pressure value. Thresholds used for generating beetle pressure are based on qualitative expert observations made during population and dispersal studies (Shore and Safranyik 1992).

Table 1. Mountain pine beetle intensity is determined using relationships that are based on beetle populations in and near the forest stand being rated (A; after Shore and Safranyik 1992). Beetle pressure is determined based on the intensity of infestation and the proximity to the infestation, or size of the overlapping Voronoi polygon (B).

A.

Number of infested trees outside stand within 3 km	Number of infested trees inside the stand		
	< 10	10–100	>100
<900	Small	Medium	Large
900 to 9,000	Medium	Medium	Large
> 9,000	Large	Large	Large

B.

Relative intensity of infestation	Within stand	Distance to nearest infestation (km)				Area of overlapping Voronoi polygon (ha)			
		0–1	1–2	2–3	3–4	>4	0–30	30–60	>60
Small	0.6	0.5	0.4	0.3	0.1	0.06	0.5	0.4	0.06
Medium	0.8	0.7	0.6	0.4	0.2	0.08	0.7	0.6	0.08
Large	1.0	0.9	0.7	0.5	0.2	0.1	0.9	0.7	0.1

The Shore and Safranyik (1992) model for calculating beetle pressure is based on the number of infested trees inside the stand, the number of infested trees outside but within 3 km of the stand, and the distance between the stand being rated and the closest infestation. For example, a stand that contains between 1 and 10 infested trees, and has 900 to 9,000 infested trees within a 3 km radius has a beetle pressure index of 0.8. If, instead, that stand contains no infested trees, and the closest infestation is between 1 and 2 km away, the beetle pressure index is 0.6 (Figure 3). The threshold values used to calculate beetle pressure are based on the results of population and dispersal studies (e.g., Safranyik 1969; Safranyik et al. 1989; Shore and Safranyik 1992; Safranyik et al. 1992).

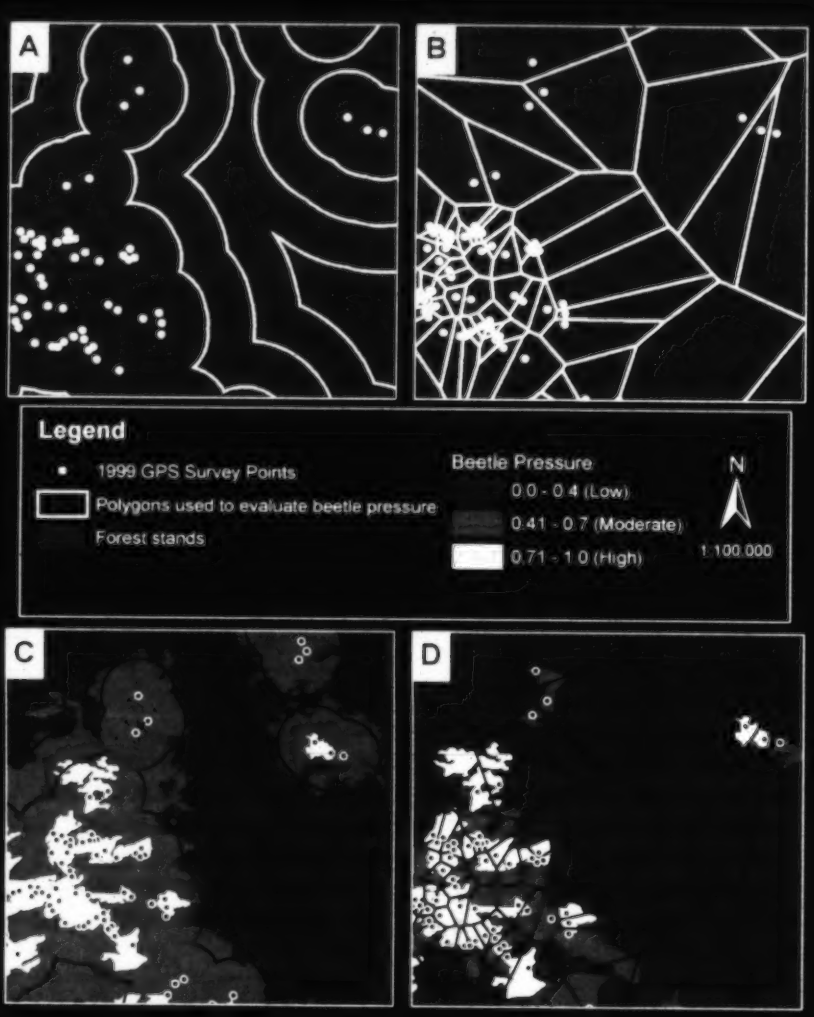


Figure 3. Examples illustrating the calculation of (A) distance- and (B) density-based models of beetle pressure. The distance-based model was generated by 1-km buffers applied to the helicopter-GPS survey points. The density-based model was generated using Voronoi polygons. The resulting beetle pressure values are shown in (C) for the distance-based model and (D) for the density-based model.

3.3 Beetle pressure using a density-based model

As an alternative to the distance-based model of beetle pressure, a density-based model was developed using Voronoi polygons (Figure 3). Given a set of points in a continuous space, Voronoi polygons partition the space in such a way that each Voronoi polygon consists of an area that is closer to a given point than any other point (Okabe et al. 2000). Survey data of known locations of beetle infestation were used to generate the Voronoi polygons using the THIESSEN command in Arc/Info™ geographic information system (GIS) software. As mentioned previously, there is an inverse proportional relationship between attack density and the size of the Voronoi polygons. These polygons of beetle density were then intersected with the forest inventory polygons; when considered in conjunction with knowledge of beetle dispersal in epidemic population conditions, they provided an indication of density-based beetle pressure for each forest stand.

Using the density-based model, beetle pressure was estimated based on the number of infested trees inside the stand, within 3 km of the stand, and the area of the Voronoi polygon overlapping the stand. The latter is unique to the density-based model. For example, a stand that contained between 1 and 10 infested trees, with 900 to 9,000 infested trees within 3 km had a beetle pressure index of 0.8—as in the distance-based model (Table 1). If, instead, the stand were to contain no infested trees, and the area of the Voronoi polygon, which intersects the stand being rated, were to be between 30 ha and 60 ha, the beetle pressure index would be 0.6 (Table 1). The 30-ha and 60-ha thresholds were developed based on spatial simulations of beetle populations and empirical mark-recapture studies. Logan et al. (1998) demonstrate that when source areas of beetles occur in high density (1 source cluster per 15 ha to 80 ha, depending on population size), spatial patterns of attacked trees replicate the clustering pattern seen in incipient and epidemic infestations. Several studies show that after release, 75% to 95% of beetles recaptured are within a 30-ha area (300-m radius), and 90% to 95% are recaptured within a 60-ha area (between a 400-m and a 500-m radius), although the percent recaptured depends on the experimental design (Safranyik et al. 1992; Turchin and Thoeny 1993; Byers 1999).

3.4 Stand risk

Risk (R) was calculated by combining the susceptibility (S) and the beetle pressure (B) components, as per Shore and Safranyik (1992):

$$R = 2.74(S^{1.77} e^{-0.0177S})(B^{2.78} e^{-2.78B}) \qquad (2)$$

Risk was modeled as the short-term probability of loss of stand basal area. High risk does not indicate that a particular stand will be attacked; rather, the stand is considered to be at greater risk than are stands with lower risk ratings. Risk ratings range from 0 to 100.

3.5 Correspondence to mountain pine beetle survey data

In order to assess the variation in beetle pressure and risk ratings generated from the distance and density approaches, the ratings for 1999 and 2000 were compared to actual locations of mountain pine beetle attack in 2000 and 2001, respectively, using GIS software. The forest inventory stand boundaries, with their estimated beetle pressure/risk ratings, were intersected with the heli-GPS survey locations. If a heli-GPS survey point was found within a forest inventory stand, the stand was considered to have been attacked by mountain pine beetle. Conversely, if no survey points were found within the stand, the stand was considered to not have been attacked. The mountain pine beetle helicopter-GPS survey data is described in Section 2.3.

4.0 Results

Of the forest stands in the study area with some level of susceptibility, the greatest proportion (28%) had a susceptibility rating less than 10 (Table 2). Stands with a low susceptibility rating (i.e., < 20) were dominated by spruce or small-diameter pine. Conversely, stands with a high susceptibility rating (*i.e.*, > 80) were dominated by large-diameter lodgepole pine. Only a small number of forest stands in the study area had high beetle pressure ratings (i.e., ≥ 0.7) for either the distance- or density-based models in 1999 or 2000 (Tables 3 and 4). The greatest differences between the two models of estimating beetle pressure occur in the low and moderate beetle pressure classes. The distance-based model for calculating beetle pressure resulted in a greater number of stands with moderate beetle pressure (Table 3), whereas the density-based model resulted in more stands with low beetle pressure (Table 4).

Table 2. Distribution of forest stands, by susceptibility rating.

Susceptibility Rating	Number of Forest Stands
0	30,681
1–10	9,558
11–20	3,911
21–30	3,083
31–40	2,640
41–50	2,308
51–60	3,193
61–70	2,488
71–80	3,279
81–90	2,167
91–100	1,227

Table 3. Distribution of forest stands, by distance-based estimates of beetle pressure.

Beetle pressure	1999	2000
High (≥ 0.7)	2,332	2,917
Moderate (0.4–0.7)	29,939	27,333
Low (≤0.4)	32,323	34,344

Table 4. Distribution of forest stands, by density-based estimates of beetle pressure.

Beetle pressure	1999	2000
High (≥ 0.7)	1,494	1,730
Moderate (0.4–0.7)	3,759	4,228
Low (≤0.4)	59,341	58,636

Results from the distance-based model showed that actual mountain pine beetle infestations occurred in stands with high, moderate, and low beetle pressure values (Table 5). However, as the beetle pressure increased, the proportion of forest stands with infestations also increased. For example, in 2000, 39.5% of stands with high beetle pressure in 1999 were attacked, whereas only 1.5% of stands with low beetle pressure values were attacked. Similarly in 2001, 31.2% of stands with high beetle pressure values were attacked in 2000, while only 4.8% of stands with low beetle pressure were attacked.

Table 5. Distance-based model of beetle pressure: number of stands in each class of beetle pressure and infestation status in the subsequent year.

Beetle pressure from 1999	Stands with attack in 2000	Stands with no attack in 2000
High (≥ 0.7)	920 (39.5%)	1,412 (60.5%)
Moderate (0.4–0.7)	2,317 (7.7%)	27,622 (92.3%)
Low (≤0.4)	480 (1.5%)	31,843 (98.5%)
Beetle pressure from 2000	**Stands with attack in 2001**	**Stands with no attack**
High (≥ 0.7)	909 (31.2%)	2008 (68.8%)
Moderate (0.4–0.7)	4,170 (15.3%)	23,163 (84.7%)
Low (≤0.4)	1,644 (4.8%)	32,701 (95.2%)

A comparable trend was found for the density-based model of beetle pressure (Table 6). In 2000, 55.1% of stands with the high beetle pressure in 1999 were attacked, whereas only 3.3% of stands with low beetle pressure were attacked. Similarly in 2001, 47.4% and 7.7% of stands with high and low beetle pressure values, respectively, in 2000 were attacked. The correspondence between actual attack and high beetle pressure was greater when the density-based model was used; however, a slightly higher rate of attack also occurred in stands with the lowest values of beetle pressure.

Table 6. Density-based model of beetle pressure: number of stands in each class of beetle pressure and infestation status in the subsequent year.

Beetle pressure from 1999	Stands with attack in 2000	Stands with no attack in 2000
High (≥ 0.7)	823 (55.1%)	671 (44.9%)
Moderate (0.4–0.7)	905 (24.1%)	2,854 (76.9%)
Low (≤ 0.4)	1,989 (3.3%)	57,352 (96.7%)
Beetle pressure from 2000	**Stands with attack in 2001**	**Stands with no attack in 2001**
High (≥ 0.7)	820 (47.4%)	910 (52.6%)
Moderate (0.4–0.7)	1,393 (32.9%)	2,835 (67.1%)
Low (≤ 0.4)	4,510 (7.7%)	54,127 (92.3%)

An assessment of how the two methods for estimating beetle pressure influenced the correspondence between risk rating and actual attack by mountain pine beetle was then undertaken. Risk ratings for 1999 and 2000 were categorized into 10-unit intervals. The proportion of stands within each risk category that were attacked or not attacked was then tabulated (Table 7). The trends for both models of beetle pressure, for both years, are very similar: as the risk rating increases, the proportion of stands with that particular risk rating that were actually attacked also increases. Furthermore, the proportion of stands with attack, for all risk ratings, was greater in 2001 than 2000. This is expected as the beetle population grows and the infestation increases in size.

Table 7. Risk Rating: Correspondence between 1999 and 2000 risk ratings and actual attack by mountain pine beetle in 2000 and 2001.

DISTANCE-MODEL

Risk Rating	Using 1999 Risk Rating		Using 2000 Risk Rating	
	Stands with attack in 2000	Stands with no attack in 2000	Stands with attack in 2001	Stands with no attack in 2001
1–10	3.88%	96.12%	7.93%	92.07%
11–20	7.81%	92.19%	14.54%	85.46%
21–30	8.21%	91.79%	13.98%	86.02%
31–40	9.61%	90.39%	15.90%	84.10%
41–50	10.85%	89.15%	19.24%	80.76%
51–60	13.17%	86.83%	21.98%	78.02%
61–70	40.50%	59.50%	49.82%	50.18%
71–80	36.38%	63.62%	49.13%	50.87%
81–90	56.09%	43.91%	49.21%	50.79%
91–100	58.29%	41.71%	72.05%	27.95%

DENSITY-MODEL

Risk Rating	Using 1999 Risk Rating		Using 2000 Risk Rating	
	Stands with attack in 2000	Stands with no attack in 2000	Stands with attack in 2001	Stands with no attack in 2001
1–10	5.54%	94.46%	10.92%	89.08%
11–20	24.90%	75.10%	37.43%	62.57%
21–30	30.42%	69.58%	34.44%	65.56%
31–40	25.47%	74.53%	31.45%	68.55%
41–50	25.06%	74.94%	37.56%	62.44%
51–60	33.00%	67.00%	40.98%	59.02%
61–70	41.22%	58.78%	50.37%	49.63%
71–80	37.01%	62.99%	54.14%	45.86%
81–90	62.72%	37.28%	54.65%	45.35%
91–100	64.51%	34.49%	75.35%	24.65%

Although the trends between the two approaches to estimating risk are similar, the density-based model generated risk estimates that had a greater correspondence with actual attack. For example, if the risk ratings are further aggregated into risk less than 50 and risk greater than 50, 18% and 27% of areas identified as having a risk rating of greater than 50 in 1999 and 2000 using the distance-based model were actually found to be attacked by beetles in surveys conducted in 2000 and 2001. Conversely, 39% and 49% of areas identified as having risk greater than 50 in 1999 and 2000 with the density-based model were attacked in 2000 and 2001. The differences between the two approaches to estimating beetle pressure and the resulting differences in risk ratings are also apparent in Figures 3 and 4, which illustrate the spatial distribution of risk for 2000. The density-based model estimated twice as much area as having risk between 0 and 10 compared to the distance-based model (477,263 ha versus 232,711 ha), whereas the distance-based model estimated 53,810 ha with risk between 11 and 20, compared to 9,925 ha with the density model.

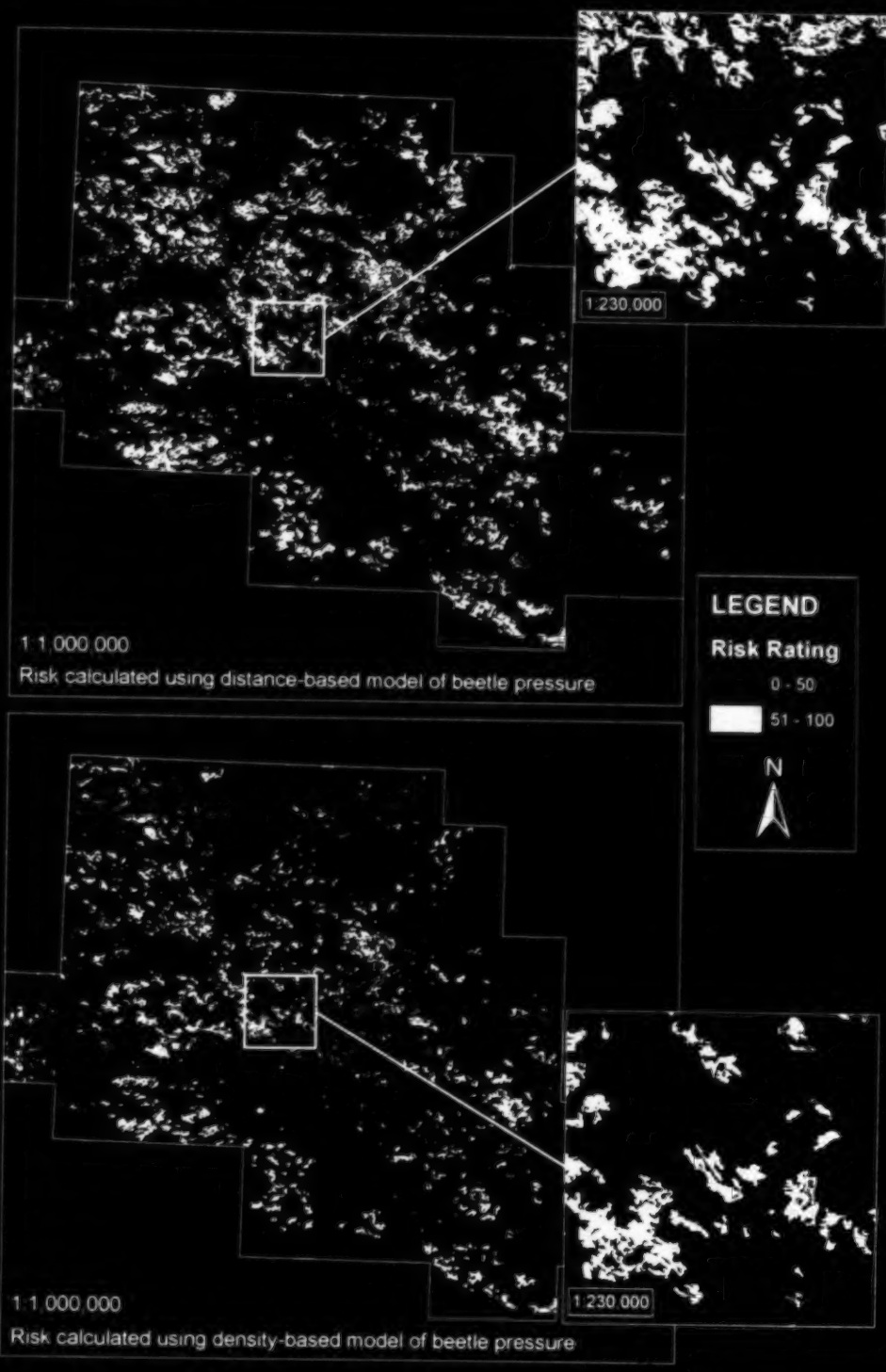


Figure 4. Risk ratings for 2000 generated using distance- and density-based models of beetle pressure.

5.0 Discussion

Beetle pressure is an important component for rating risk of mountain pine beetle attack. Two different approaches to estimating beetle pressure were tested for comparison. Although both approaches accounted for dispersal distances and infestation size, the distance-based model emphasized the distance between the stand being evaluated and the nearest infestation, whereas the density-based model emphasized the density of infestation points around the stand being evaluated. Overall, the density-based model of beetle pressure, developed using Voronoi polygons, generated high risk ratings that more closely corresponded with actual attack by mountain pine beetle.

A number of factors may have confounded results where stands experiencing high beetle pressure (and which had a high risk rating) were not attacked in the subsequent year. It is difficult to predict the outcome of natural processes such as dispersal and population dynamics of mountain pine beetle. An additional factor in this study area may have been the depletion of resources (Safranyik et al. 1974), as the mountain pine beetle epidemic in the Fort St. James Forest District started before the 1999 base year for this research (British Columbia Ministry of Forests 2002). Forest harvesting, as a component of an insect mitigation strategy (salvage harvesting), would also act to reduce the number of possible insect hosts. In the case where a forest inventory is outdated, it is possible that susceptibility would be overestimated, minimizing sensitivity to beetle pressure, and resulting in an overestimation of risk.

Similarly, there are several potential reasons why stands with low risk ratings were attacked. As was previously mentioned, in epidemic population conditions, when competition for suitable hosts increases, beetles will attack sub-optimal hosts (Safranyik and Carroll 2006). Furthermore, since outbreak conditions existed in much of the region surrounding the study area in the years considered (1999 to 2002), beetles could have emigrated from other areas via some long range dispersal mechanism (Safranyik and Carroll 2006). Such an influx would exacerbate beetle pressure. It should also be noted that the helicopter-GPS surveys were not conducted in a systematic manner across the study area, and that no information was recorded for locations where there was no attack. Therefore, for the purposes of this analysis, an assumption was made that stands that did not contain any survey points were not attacked. Notwithstanding the potential for error associated with this assumption, the helicopter-GPS survey data is the benchmark of mountain pine beetle survey information (Wulder et al. 2006b), and has generally been found to be accurate in detecting locations of red-attack damage (Nelson et al. 2006).

The calculation of beetle pressure depends on a number of assumptions, including: dispersal distances, dispersal directionality, and population density of mountain pine beetle. Further research in these areas could reduce the uncertainty in the model output (Higgins et al. 2003). Dispersal distances have been measured and modeled below the forest canopy (Safranyik et al. 1992; Powell et al. 2000). However, a large percentage of the population remains unaccounted for, and little is known about dispersal above the canopy (Safranyik et al. 1992; Barclay et al. 1998). When calculating beetle pressure, the beetles are assumed to disperse equally in all directions; however, since they are largely moved passively by the wind, the dispersal may follow from the predominant wind direction (Byers 2000). The interactions between population size, aggregation, disaggregation, and resource depletion are being researched and modeled at the local scale (Logan et al. 1998; Safranyik et al. 1999). A mountain pine beetle infestation represents a complex natural process, impacting large areas both ecologically and economically. Ongoing research is attempting to improve the characterization of mountain pine beetle movement spatially and temporally at the landscape scale (Safranyik and Wilson 2006).

Although there are comparable trends between the two risk rating outputs, the distance-based model of beetle pressure identified more stands with a higher risk rating than did the density-based model. The Voronoi polygons used in the density-based model incorporated the density of the helicopter-GPS survey points into the estimates of beetle pressure. When beetle populations are increasing, more areas of damage will be identified in the survey, thereby increasing the density of the survey points and resulting in smaller Voronoi polygons, which in turn result in a more spatially constrained rating of risk. With the

distance-based model, the density of the survey points has no bearing on beetle pressure. In an operational context, a forest manager will want to prioritize areas for mitigation as resources will typically be limited. Using the distance-based model, a much larger area would require action. However, by incorporating knowledge of beetle population dynamics and accounting for the density of survey points through spatial analysis, a spatially refined rating of risk results. We hypothesize that the density-based model is effective when mountain pine beetle populations are increasing and the density of surveyed damage is also increasing. Therefore, under certain population conditions, it may be preferable to emphasize the density of, rather than the distance to, nearby beetle infestations. Further testing of the density-based model under a range of population conditions are needed to test this hypothesis.

6.0 Conclusion

Assessing the stand-level risk associated with mountain pine beetle attack is a useful tool for predicting where attack is most likely to occur. Such information may be used by forest managers to prioritize areas for mitigation efforts. Risk is a function of stand susceptibility and beetle pressure, with the latter typically being calculated by considering the distance and size of mountain pine beetle populations within a certain proximity to the stand being rated. An alternate approach to calculating beetle pressure that considers the size, distance, and density of beetle populations was presented in this paper. Voronoi polygons represent the density of attack by mountain pine beetle in an intuitive manner: the inverse proportional relationship between the size of the Voronoi polygon and the density of attack facilitates interpretation. Previous research has indicated that high density population-source areas may increase the risk of attack, primarily as a result of the massive number of beetles dispersing across the landscape. Given this, density may be an alternate means to estimate beetle pressure under epidemic population scenarios, although the approach presented herein would require testing under a broader range of population and stand-level conditions before being implemented operationally. In our study area, risk ratings generated from the density-based model of beetle pressure corresponded more closely with actual beetle attack locations in the subsequent year, when compared to risk ratings generated from a distance-based model.

Acknowledgements

This project is funded by the Government of Canada through the Mountain Pine Beetle Initiative, a six-year, $40-million program administered by Natural Resources Canada, Canadian Forest Service. Additional information on the Mountain Pine Beetle Initiative may be found at: http://mpb.cfs.nrcan.gc.ca/. Tim Ebata, of the British Columbia Ministry of Forests and Range, is thanked for provision of GPS survey data.

Contact

Michael A. Wulder
Natural Resources Canada
Canadian Forest Service
Pacific Forestry Centre
Victoria, BC V8Z 1M5
Telephone: 250-363-6090; fax: 250-363-0775; email: mwulder@nrcan.gc.ca

References

Amman, G.D.; McGregor, M.D.; Cahill, D.B.; Klein, W.H. 1977. Guidelines for reducing losses of lodgepole pine to the mountain pine beetle in unmanaged stands in the Rocky Mountains. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-36. 19 p.

Amman, G.D. 1982. The Mountain Pine Beetle: Identification, Biology, Causes of Outbreaks, and Entomological Research Needs. *Pages* 7–12 *in:* Shrimpton, D.M. (Ed.), Proceedings of the Joint Canada/USA Workshop on Mountain Pine Beetle Related Problems in Western North America, Environment Canada, Canadian Forestry Service, Pacific Forest Research Centre, Victoria, British Columbia, Canada. Information Report BC-X-230. 87 p.

Amman, G.D.; Cole, W.E. 1983. Mountain pine beetle dynamics in lodgepole pine forests part 2: Population dynamics. United States Department of Agriculture Forest Service GTR-INT-145, 59 p.

Anhold, J.A.; Jenkins, M.J. (1987). Potential mountain pine beetle (Coleoptera: Scolytidae) attack of lodgepole pine as described by stand index. Environmental Entomology 16:738–742.

Barclay, H.J.; Safranyik, L.; Linton, D. 1998. Trapping mountain pine beetles *Dendroctonus ponderosae* (Coleoptera: Scolytidae) using pheromone-baited traps: effects of trapping distance. Journal of the Entomological Society of British Columbia. 95, 25–31.

Bentz, B.J.; Amman, G.D.; Logan, J.A. 1993. A critical assessment of risk classification systems for the mountain pine beetle. Forest Ecology and Management 61:349–366.

Berryman, A.A. 1978. A synoptic model of the lodgepole pine/mountain pine beetle interaction and its potential application in forest management. *Pages* 98–103 *in* Berryman, A.A.; Amman, G.D.; Stark, R.W.; Kibbee, D.L., eds. Proceedings: Theory and practice of mountain pine beetle management in lodgepole pine forests. April 25–27, 1978, Pullman, WA. University of Idaho, Moscow, ID, 224 p.

Boots, B.N.; Getis, A. 1988. *Point Pattern Analysis*. Scientific Geography Series, Volume 8. Newbury Park, Ca.: Sage Publications. 93 p.

British Columbia Ministry of Forests. 1995. Bark beetle management guidebook (Forest Practices Code) Forest Practices Branch, Victoria, British Columbia, Canada. 45 p. www.for.gov.BC.ca/tasb/legsregs/fpc/fpcguide/beetle/betletoc.htm (Accessed 30th January 2006).

British Columbia Ministry of Forests. 2002. Historical distribution of damage mountain pine beetle cumulative damage history from about 1959 to 2002. http://www.for.gov.bc.ca/hfp/forsite/overview/mpb_history.htm (accessed September 2006).

British Columbia Ministry of Forests. 2004. British Columbia Ministry of Forests Land-Base Investment Program: Aerial Detection Standards for Bark Beetle Management. Interim for Fiscal Year 2004–2005. http://www.for.gov.bc.ca/hcp/fia/landbase/AerialDetectionStandardforBarkBeetleManagement.doc (accessed September 2006).

British Columbia Ministry of Sustainable Resource Management. 2002. Gridded digital elevation model product specifications. Edition 2.0. Base Mapping and Geomatics Services Branch, Victoria, B.C. http://ilmbwww.gov.bc.ca/bmgs/products/BC-DEM-specifications-2002-12.pdf (accessed September 2006).

Byers, J.A. 1999. Effects of attraction radius and flight paths on catch of Scolytid beetles dispersing outward through rings of pheromone traps. Journal of Chemical Ecology 25:985–1005.

Byers, J.A. 2000. Wind-aided dispersal of simulated bark beetles flying through forests. Ecological Modelling 125:231–243.

Carroll, A.L.; Taylor, S.W.; Régnière, J.; Safranyik, L. 2004. Effects of climate change on range expansion by the mountain pine beetle in British Columbia. *Pages* 223–232 *in:* Shore, T.L. Brooks, J.E., Stone, J.E. (Eds.), Mountain Pine Beetle Symposium: Challenges and Solutions, October 30–31, 2003, Kelowna, British Columbia, Canada. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, Information Report BC-X-399. 298 p.

Furniss, R.L.; Carolin, V.M. 1977. Western Forest Insects. United States Department of Agriculture Forest Service Miscellaneous Publication Number 1339. 654 p.

Gillis, M.D.; Leckie, D.G. 1993. Forest inventory mapping procedures across Canada. Information Report PI–X–114, Petawawa National Forestry Institute, Forestry Canada. 74 p.

Gillis, M.D.; Leckie, D.G. 1996. Forest inventory update in Canada. Forestry Chronicle 72:138–156.

Hawksworth, F.G.; Williams-Cipriani, J.C.; Eav, B.B.; Geils, B.G.; Johnson, R.R.; Marsden, M.A.; Beatty, J.S.,; Shubert, G.S.; Robinson, D.C.E. 1995. Dwarf Mistletoe Impact Modeling System User's Guide and Reference Manual. United States Department of Agriculture Forest Service Report MAG-95-2. 120 p.

Henigman, J.; Ebata, T.; Allen, E.; Pollard, A. (Eds.). 1999. Field Guide to Forest Damage in British Columbia. British Columbia Ministry of Forests, Victoria, BC. 343 p.

Higgins, S.I.; Clark, J.S.; Nathan, R.; Hovestadt, T.; Schurr, F.; Fragoso, J.M.V.; Aguiar, M.R.; Ribbens, E.; Lavorel, S. 2003. Forecasting plant migration rates: managing uncertainty for risk assessment. Journal of Ecology 91:341–347.

Leckie, D.; Cloney, E.; Joyce, S. 2005. Automated detection and mapping of crown discolouration caused by jack pine budworm with 2.5 m resolution multispectral imagery. International Journal of Applied Earth Observation and Geoinformation 7:61–77.

Liu, D.; Kelly, M.; Gong, P. 2006. A spatial-temporal approach to monitoring forest disease spread using multi-temporal high spatial resolution imagery. Remote Sensing of Environment 101:167–180.

Logan, J.A.; White, P.; Bentz, B.J.; Powell, J.A. 1998. Model analysis of spatial patterns in mountain pine beetle outbreaks. Theoretical Population Biology 53:236–255.

Mahoney, R.L. 1978. Lodgepole pine/mountain pine beetle risk classification methods and their application. Pages 106-113 *in* Berryman, A.A.; Amman, G.D.; Stark, R.W.; Kibbee, D.L., eds. Proceedings: Theory and practice of mountain pine beetle management in lodgepole pine forests. April 25-27, 1978, Pullman, WA. University of Idaho, Moscow, ID. 224 p.

Meidinger, D.; Pojar, J. (Eds). 1991. *Ecosystems of British Columbia*. Research Branch, Ministry of Forests, Victoria, British Columbia, Canada. 330 p.

Nelson, T.; Boots, B.; Wulder, M.A. 2006. Large-area mountain pine beetle infestations: Spatial data representation and accuracy. The Forestry Chronicle. 82, 243–252.

Okabe, A.; Boots, B.; Sugihara, K.; Chiu, S.N. 2000. Spatial tessellations: Concepts and applications of Voronoi diagrams, 2nd edition. John Wiley & Sons. 671 p.

Pedersen, L. 2002. Prince George Timber Supply Area: Rationale for Allowable Annual Cut (AAC) Determination, Effective June 1, 2002. British Columbia Ministry of Forests, Victoria, British Columbia. 100 p.

Pedersen, L. 2004. Prince George Timber Supply Area: Rationale for Allowable Annual Cut (AAC) Determination, Effective October 1, 2004. British Columbia Ministry of Forests, Victoria, British Columbia. 63 p.

Pousette, J.; Hawkins, C. 2006. An assessment of critical assumptions supporting the timber supply modelling for mountain-pine-beetle-induced allowable annual cut uplift in the Prince George Timber Supply Area. BC Journal of Ecosystems and Management 7:93–104. http://www.forrex.org/publications/jem/ISS35/vol7_no2_art10.pdf (accessed September 2006).

Powell, J.; Kennedy, B.; White, P.; Bentz, B.; Logan, J.; Roberts, D. 2000. Mathematical elements of attack risk analysis for mountain pine beetles. Journal of Theoretical Biology 204:601–620.

Safranyik, L. 1969. Development of a technique for sampling mountain pine beetle populations in lodgepole pine. Ph.D. Thesis. Univeristy of British Columbia, Vancouver BC. 195 p.

Safranyik, L.; Shrimpton, D.; Whitney, H. 1974. Management of lodgepole pine to reduce losses from the mountain pine beetle. Canadian Forest Service, Victoria, British Columbia. Forestry Technical Report. 23 p.

Safranyik, L.; Silversides, R.; McMullen, L.H.; Linton, D.A. 1989. An empirical approach to modeling the local dispersal of the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) Col., Scolytidae) in relation to sources of attraction, wind direction and speed. Journal of Applied Entomology 108:498–511.

Safranyik, L.; Linton, D.A.; Silversides, R.; McMullen, L.H. 1992. Dispersal of released mountain pine beetles under the canopy of a mature lodgepole pine stand. Journal of Applied Entomology 113:441–450.

Safranyik, L.; Barclay, H.; Thomson, A.; Riel, W.G. 1999. A population dynamics model for the mountain pine beetle, *Dendroctonus ponderosae* Hopk. (Coleoptera : Scolytidae). Canadian Forest Service, Victoria, British Columbia. Information Report BC-X-386. 24 p.

Safranyik, L.; Carroll, A. 2006. The biology and epidemeology of the mountain pine beetle in lodgepole pine forests. *Pages* 3–66 *in:* L. Safranyik and B. Wilson (Eds.) The Mountain pine beetle: A synthesis of biology, management, and impacts on lodgepole pine. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, Canada. 304 p.

Safranyik, L.; Wilson, B. 2006. The Mountain pine beetle: A synthesis of biology, management, and impacts on lodgepole pine. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, Canada. 304 p.

Schenk, J.L.; Mahoney, R.L.; Moore, J.A.; Adams, D.L. 1980. A model for hazard rating lodgepole pine stands for mortality by mountain pine beetle. Forest Ecology and Management 3:57–66.

Shore, T.L.; Safranyik, L. 1992. Susceptibility and risk rating systems for the mountain pine beetle in lodgepole pine stands. Forestry Canada, Victoria, British Columbia. Information Report BC-X-336. 12 p.

Shore, T.L.; Safranyik, L.; Lemieux, J.P. 2000. Susceptibility of lodgepole pine stands to the mountain pine beetle: testing of a rating system. Canadian Journal of Forest Research 30:44–49.

Shore, T.L.; Riel, B.G.; Safranyik, L.; Fall, A. 2006. Decision support systems. *Pages* 193–230 *in:* L. Safranyik and B. Wilson (Eds.), The Mountain pine beetle: A synthesis of biology, management, and impacts on lodgepole pine. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, Canada. 304 p.

Stuart, J.D. 1984. Hazard rating of lodgepole pine stands to mountain pine beetle outbreaks in southcentral Oregon. Canadian Journal of Forest Research 14:666–671.

Taylor, S.W.; Carroll, A.L. 2004. Disturbance, forest age, and mountain pine beetle outbreak dynamics in BC: A historical perspective. *Pages* 41–51 *in:* T.L. Shore, J.E. Brooks, and J.E. Stone, editors. Mountain Pine Beetle Symposium: Challenges and Solutions, October 30–31, 2003, Kelowna, British Columbia, Canada. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, Information Report BC-X-399. 298 p.

Turchin, P.; Theony, W.T. 1993. Quantifying dispersal of southern pine beetles with mark-recapture experiments and a diffusion model. Ecological Applications 3:187–198.

Waring, R.H.; Pitman, G.B. 1980. A simple model of host resistance to bark beetles. Forest Research Laboratory Research Note 65, Oregon State University, School of Forestry, OR.

Westfall, J. 2006. 2005 summary of forest health conditions in British Columbia. British Columbia Ministry of Forests and Range, Forest Practices Branch, Victoria, British Columbia. Pest Management Report Number 15. 50 p.

Wulder, M.A.; Dymond, C.C.; White, J.C.; Leckie, D.G.; Carroll, A.L. 2006a. Surveying mountain pine beetle damage of forests: A review of remote sensing opportunities. Forest Ecology and Management 221:27–41.

Wulder, M.A.; White, J.C.; Bentz, B.J.; Ebata, T. 2006b. Augmenting the existing survey hierarchy for mountain pine beetle red-attack damage with satellite remotely sensed data. Forestry Chronicle 82:187–202.

This publication is funded by the Government of Canada through the Mountain Pine Beetle Initiative, a program administered by Natural Resources Canada, Canadian Forest Service (web site: mpb.cfs.nrcan.gc.ca).

Contact:

For more information on the Canadian Forest Service, visit our web site at:
www.nrcan.gc.ca/cfs-scf

or contact the Pacific Forestry Centre
506 West Burnside Road
Victoria, BC V8Z 1M5
Tel: (250) 363-0600 Fax: (250) 363-0775
www.pfc.cfs.nrcan.gc.ca

To order publications on-line, visit the Canadian Forest Service Bookstore at:
bookstore.cfs.nrcan.gc.ca